DETERMINATION OF BURST PRESSURE OF DEFECTIVE STEEL PIPES USING FINITE ELEMENT ANALYSIS

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ABSTRACT

This thesis deals with assessment of defective API 5L X65 steel pipes which are widely used in product transportation in oil and gas industry. The objective of the thesis is to determine the burst pressure of defective API X65 steel pipes under the effect of gouge length for different pipe diameter. The thesis describes the finite element analysis techniques to predict the true fracture and identify the critical locations of the structures (pipe). One-quarter three-dimensional solid modelling of steel pipe was developed using the MSC Patran 2008r1 that act as a pre-processor. The finite element analysis was then performed using MSC Marc. The finite element model of the pipe was analyzed using the non-linear isotropic elasto-plastic material that obeys the incremental of plastic theory. The values of principal stresses and strains acted on the critical location of gouge defect had been obtained by MSC Patran as a post-processor. The values were used to determine the true fracture strain which is known to be exponentially dependent to the stress triaxiality. Finally, burst pressure was determined as the true fracture strain exceeds the value of equivalent strain at that instant point. Based on the results, it is observed that the analysis using SMCS model yields more conservative burst pressure prediction. The obtained results indicate that the shorter gouge length would gives higher burst pressure which means, higher pressure needed as the pipe to experience failure at the gouge defect area. Result shows that the burst pressure decreases with increment of pipe diameter. The results concluded that the shorter gouge length and smaller pipe diameter conditions give the highest pressure value of pipe burst. Therefore, the defect characteristic is the promising criteria to increase the fitness of service of the pipe.

ABSTRAK

Tesis ini berkaitan dengan penilaian kecacatan bagi paip keluli API 5L X65 yang digunakan secara meluas untuk pengangkutan produk dalam industri minyak dan gas. Objektif tesis ini adalah untuk menentukan tekanan maksimum yang boleh ditanggung oleh paip keluli API X65 yang mengandungi kecacatan (gouge) dengan diameter paip yang berbeza. Tesis menerangkan teknik-teknik analisis unsur terhingga untuk meramalkan patah sebenar dan mengenal pasti lokasi kritikal struktur (paip). Satu-perempat tiga-dimensi pemodelan paip keluli telah dibangunkan dengan menggunakan MSC Patran 2008r1 yang bertindak sebagai pra-pemproses. Analisis unsur terhingga telah dilakukan menggunakan penyelesai MSC Marc. Model unsur terhingga paip telah dianalisis dengan menggunakan bahan yang mempunyai ciri-ciri isotropi elastic-plastik yang mengikut kepada peningkatan teori plastik. Nilai-nilai tegasan dan terikan utama bertindak di lokasi kritikal kecacatan telah diperolehi oleh MSC Patran yang digunakan sebagai pasca-pemproses. Nilai-nilai tersebut telah digunakan untuk menentukan terikan patah sebenar yang juga eksponen bergantung kepada tekanan tiga paksi. Akhirnya, tekanan pecah ditentukan sebagai terikan patah benar melebihi nilai terikan pada titik tersebut. Berdasarkan keputusan, ia diperhatikan bahawa analisis yang menggunakan model SMCS menghasilkan ramalan tekanan pecah yang lebih konservatif. Keputusan yang diperolehi menunjukkan bahawa kecacatan (gouge) yang lebih pendek akan memberikan tekanan pecah yang lebih tinggi. Keputusan menunjukkan bahawa tekanan pecah berkurangan dengan pembesaran saiz paip. Keputusan yang diperolehi menyimpulkan bahawa kecacatan yang pendek dan diameter paip yang lebih kecil memberikan nilai tekanan tertinggi sebelum paip pecah. Oleh itu, ciri-ciri kecacatan adalah kriteria yang menjanjikan untuk keselamatan paip yang boleh digunakan.

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LIST OF SYMBOLS

σ	Stress
σ_u	Ultimate Tensile Strength
σ_y	Yield Strength
σ_h	Hoop Stress
σ_r	Radial Stress
σ_l	Longitudinal Stress
ε	Strain
ε_{ef}	True Fracture Strain
E	Young Modulus
v	Poisson Ratio
λ	Shell Parameter
M_t	Folias Stress Magnification Factor
π	PI
τ	Shear Stress

LIST OF ABBREVIATIONS

API	American Petroleum Institute
FE	Finite Element
FFS	Fitness for Service
ID	Internal Diameter
OD	Outer Diameter
RP	Recommended Practice
SMSC	Stress-Modified Critical Strain
UTS	Ultimate Tensile Strength

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

American Petroleum Institute (API) has classified the pipe for oil and gas. API X65 steel pipe is one of the pipes that is has been standardized by API and it was largely used in oil and gas industries. It was used as underground pipelines to transport the product of oil and gas. Underwater and underground position of the steel pipe makes it exposed to the salty environment and damp surrounding which can cause corrosion. During the installation of the pipelines, third party accidents could happen and caused dents and gouges to the pipelines due to contact of steel-steel and also minor scratches on the pipe. This thesis will apply the ductile failure criteria proposed by C.-K.Oh et al. (2007); on gouged API X65 steel pipes in terms of true fracture strain as a function to the stress triaxiality (defined by the ratio of the hydrostatic stress to the equivalent stress). To determine the true fracture strain of the pipe, a finite element (FE) modeling (MSC Patran 2008 r1) of smooth and gouged steel pipe with different gouge length are tested using FE analysis (MSC Marc). Simulation was made to emulate the variation of stress triaxiality of the ductile behavior on the material.

From the elastic-plastic deformation of the material, variation of stress triaxiality which leads to true fracture strains as a function of stress triaxiality can be obtained and used to determine the burst pressure of a gouged steel pipes. By applying this burst pressure equation, the stresses subjected to the material due to the internal pressure of the pipe and the other stresses involved on outer surface of the pipe can be determined.

But, in this thesis, the intention goes to the burst pressure of the API X65 steel pipes can withstand under the defective condition.

1.2 OBJECTIVES OF THE RESEARCH

The main objectives of this project are as follow:

1) To determine the burst pressure of defective API X65 steel pipes.

2) To investigate the effect of gouge length and pipe outer diameter on burst pressure.

1.3 SCOPE OF PROJECT

The scope of this project concentrates about the determination of burst pressure of defective steel pipes. API X65 steel pipes with the minimum specified yield strength and ultimate tensile strength are σ_y = 448 MPa and UTS = 530 MPa was used for subjecting the test of the burst pressure. The defect was interpreted as a gouge on the surface of the steel pipe. Different gouge length was studied to investigate its effect on the burst pressure of the steel pipes. MSC Patran/Marc was used for FE analysis to by applying the elasto-plastic isotropic homogeneous material model with reduced integration. A one-quarter model has been used to represent the full-scale model of the pipe for computational efficiency

1.4 PROBLEM STATEMENT

API X65 steel pipes is primarily used in the oil and gas industries. The ductility, high strength and low cost; makes it much more attractive than other type of steel pipe. Higher-performing steel was used since these industries routinely use miles of pipe. During the installation of the pipelines, defects are seldom happen which caused by the third party accidents such as dents and gouges. The pipeline was exposed to the environment salty sea water and makes it always exposed to the corrosive media. Corrosion happens, can cause the reduction in thickness of the pipe or in other words is called metal loss. Metal loss can be very dangerous to the pipeline and which could cause burst. For this thesis, metal loss from the pipe can be represented as a gouge on the surface of the pipe.

In order to maintain the integrity of the pipe, the burst pressure becomes the main parameter to be determined. The method to determine the burst pressure was by using FE analysis software. FE analysis was chosen rather than experimental analysis because experimental method is very complicated to be done. It requires some expensive equipment and material. Proper location of experiment is also need to be considered and it must be equipped with safety measures and acoustic proof, because the experiment will produce an explosion noise from the burst on the gouge. Using FE analysis, the test can be done with only by modeling and analyze the model.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

A pipe is a tubular section or hollow cylinder, usually but not necessarily of circular cross-section, used mainly to convey substances which can flow — liquids and gases (fluids), slurries, powders, masses of small solids. It can also be used for structural applications; hollow pipe is far stiffer per unit weight than solid members. Pipes are utilized in various industries and applications. Such usages of steel pipes are for pipe pilling, road boring, floating docks, fencing, penstock, fiber-optics and drilling.

Some of oil pipeline applications are, oil pipeline API SPEC 5L for the purpose of transportation of gas, water, oil in oil & gas industry. API SPEC 5CT tubing is used in extracting petroleum & natural gas casing pipe serves as wall of well. ASTM A106 for the purpose of the pipeline project of boiler, water & petroleum. ASTM A53 it is used for conveying water, petroleum, gas and other common fluids. ASTM A179 for tubed heat exchanger and similar heat conveying equipments. ASTM A192 for manufacture wall panel, economizer, reheater, superheater and steam pipeline of boilers.

In oil and gas industry, most transportation of oil and as product uses a seamless steel pipes. Seamless steel pipes are a kind of hollow cross-section with no surrounding joints. It can be used for transmitting a large number of fluids such as oil, natural gas, water and some solid materials. At the same time it can be widely used as the manufacture of various structural parts and mechanical parts, such as the drill pipe, automotive transmission shaft, as well as building construction. Compared with the solid steel such as round bar, at the same flexural torsional strength, the weight of Seamless steel pipe is lighter. It is a type of economic steel.

2.2 HISTORY

Fracture mechanics is a field of mechanics, concerned with the study of the propagation of cracks in materials. It uses methods of analytical solid mechanics to calculate the driving force on a crack and those of experimental solid mechanics to characterize the material's resistance to fracture. Most engineering materials were having ductile behavior, and shows some nonlinear elastic and inelastic deformation under operating conditions that involve larger loads. In such material, the assumptions of linear elastic fracture mechanics may not hold because of the plastic zone at a crack tip may have a size of the same order of magnitude as the crack size and the size and shape of the plastic zone may change as the applied force is increased and also as the crack length increases.

Therefore, a more general theory of crack growth is needed for elastic-plastic materials that can account for the local conditions for initial crack growth which includes the nucleation, growth and coalescence of voids or decohesion at the crack tip.

2.3 API 5L X65

API 5L X65 steel pipes was generally used as a medium to transport the hydrocarbon products from off-shore to on-shore or on the ground eventually. One interesting point is that, as most of the API X65 gas pipelines in Korea have been built within the last 10 years, mechanical properties of API X65 gas pipelines in Korea tend to have quite uniform properties (Oh C-K et al, 2007). Table 2.1 and 2.2 are the properties of API X65 steel pipe used in this thesis project.

Table 2.1: Chemical composition of the API X65 steel

Element (wt %)						
C	P	Mn	S	Si	Fe	Ceq
0.08	0.019	1.45	0.03	0.31	Balance	0.32

Source: American Petroleum Institute (2000)

Table 2.2: Mechanical tensile properties at room temperature of the API X65 steel

Young's modulus *E (GPa)*	Poisson's Ratio v	Yield strength σ_y *(MPa)*	Tensile strength σ_u *(MPa)*
210.7	0.3	464.5	563.8

Source: American Petroleum Institute (2000)

2.4 TYPE OF DEFECTS ON STEEL PIPES

Oil and gas transmission pipelines have a good safety record and are a demonstrably safe means of transporting hydrocarbons. This is due to a combination of good design, materials and operating practices. However, like any engineering structure, pipelines do occasionally fail. The major causes of pipeline failures around the world are external interference and corrosion; therefore, assessment methods are needed to determine the severity of such defects when they are detected in pipelines (Cosham A, 2004). Assessment methods and determination of the burst pressure before a total lost could occur are needed to determine the rigorousness of such defects when they are detected in pipelines.

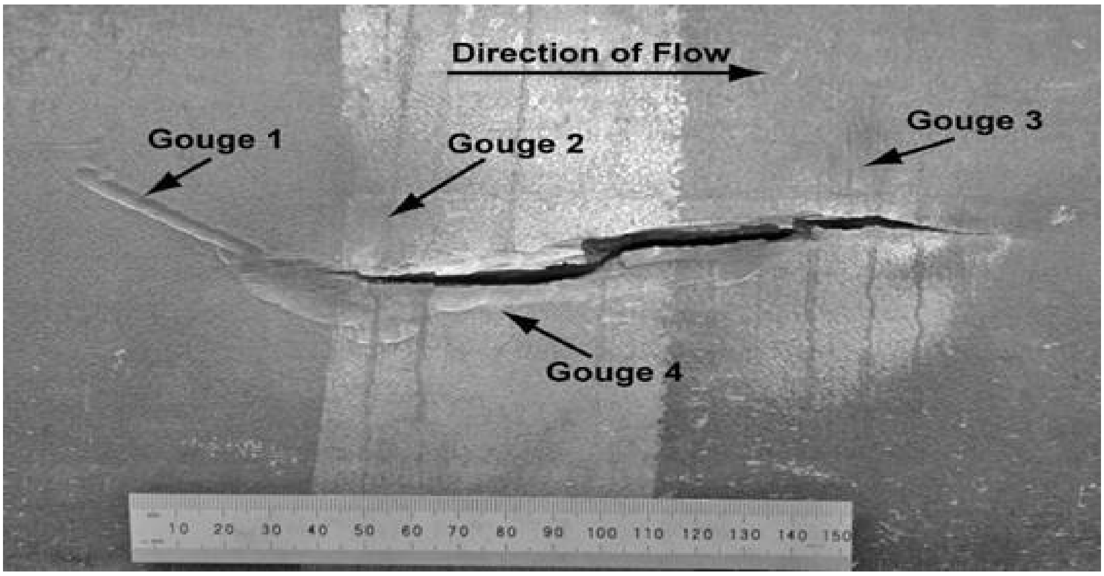

Figure 2.1: Gouged steel pipe

Source: Cosham A, 2004

2.4.1 Gouge

A gouge is defended as a type of chisel with a blade that has a concavo-convex section. Upon the corrosion process, metal loss from the steel pipe can occur and cause gouges on the outer surface or inner surface of the pipe. Because of the outer surface of the steel pipe is much exposed by the surrounding, the corrosion process are more likely to happen rather than the inner surface. As the gouges happen on the surface of the pipe, the wall thickness of the steel pipe could reduce and eventually cause in irregularity of the total shape of that particular pipe.

2.4.2 Dent

A dent in a pipeline is a permanent plastic deformation of the circular cross-section of the pipe and it is a gross distortion of the pipe cross-section (Cosham A and Hopkins P, 2004). Dent depth is defined as the maximum reduction in the diameter of the pipe compared to the original diameter. A dent would cause a local stress and strain concentration, and a local reduction in the pipe diameter. The dent depth is the most major factor affecting the burst strength and the fatigue life of a plain dent. The profile of the dent does not emerge to be a vital parameter, as long as the dent is smooth.

Whether a pipe is gouged during indentation depends on many factors, including the curve of the indentation, the frictional resistance between the surface of the pipe and the indenter, the shape and sharpness of the indenter, the pipe geometry, the material properties and the internal pressure. The stiffer the pipe, the more resistant it is to denting. Damage introduced into pressurized pipe tends to comprise shallower dents and deeper gouges than damage introduced into unpressurized pipe, because internal pressure stiffens the pipe. A sharp indenter is more likely to cut into the pipe wall when the pipe is pressurized. Experimentally it has been observed that coated and lubricated pipe surfaces prolong less damage than do dry, bare pipe surfaces.

2.4.3 Corrosion

Corrosion is an electrochemical process. It is a time dependent mechanism and depends on the local environment within or adjacent to the pipeline. Corrosion usual appears as either general corrosion or localized (pitting) corrosion. There are many different types of corrosion, including galvanic corrosion, microbiologically induced corrosion, AC corrosion, differential soils, differential aeration and cracking. Corrosion causes metal loss.

Corrosion in a pipeline may be difficult to characterize. Typically, it will have an irregular depth profile and extend in irregular pattern in both longitudinal and circumferential directions. It may occur as a single defect or as a cluster of adjacent defects separated by full thickness (un-corroded) material. There are no clear definitions of different types of corrosion defects. The simplest and perhaps most widely recognized definitions are as follows: pitting corrosion, defined as corrosion with a length and width less than or equal to three times the un-corroded wall thickness, and general corrosion, defined as corrosion with a length and width greater than three times the un-corroded wall thickness.

2.5 STRESSES ACTED ON STEEL PIPES

A broadly accepted method of predicting tubing failure due to pressure and tension limits is based on the von Mises stress. If the von Mises stress exceeds the yield strength of the material, the tubing is assumed to fail. The von Mises stress is a combination of the three principal stresses in and the shear stress caused by torque. The three principal stresses are axial stress (σ_a), radial stress (σ_r) and Tangential or hoop stress (σ_h). There are two types of assumptions made in analyzing these principle stresses. Those are thin-walled pressure vessel and thick walled pressure vessels. Thin-walled pressure vessel can be assumed when the ratio of $\frac{r}{t} \geq 10$. Generally, a pressure vessel is considered to be thin-walled if its radius, *r* is larger or equal than 10 times its wall thickness, *t.* On the other hand, it was assumed that for thick-walled pressure vessel must have a ratio of $\frac{r}{t} \leq 10$. That means the pressure vessel is considered to be thin-walled if its radius, *r* is smaller or equal than 10 times its wall thickness, *t.*

The coordinates used to describe the cylindrical vessel can take advantage of its axial symmetry. It is natural to align one coordinate along the axis of the vessel in the longitudinal direction). To analyze the stress state in the vessel wall, a second coordinate is then aligned along the hoop direction. With this choice of axisymmetric coordinates, there is no shear stress. The hoop stress σ_h and the longitudinal stress σ_l are the principal stresses.

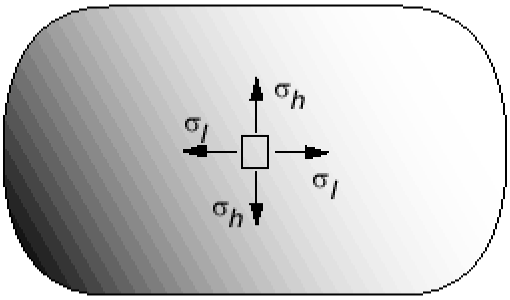

Figure 2.2: Direction of hoop and longitudinal stress

Source: Beer FP, Jr. Johnston ER, De Wolf JT (2006)

2.5.1 Hoop Stress

A circumferential stress which, in a pipe or pressure vessel would tend to make the pipe diameter or circumference increases. As fluid which has filled the pipe is pressurized the hoop stress causes the diameter or circumference to increase. The force resisted by the tangential stress can be called as *hoop stress* and it is acting uniformly over the stressed area for thin-walled pressure vessel. The free body is in static equilibrium. According to Newton's first law of motion, the hoop stress yields;

$$2 \cdot \sigma_h \cdot t \cdot dx = p \cdot 2 \cdot r \cdot dx \tag{2.1}$$

$$\sigma_h = \frac{pr}{t} \tag{2.2}$$

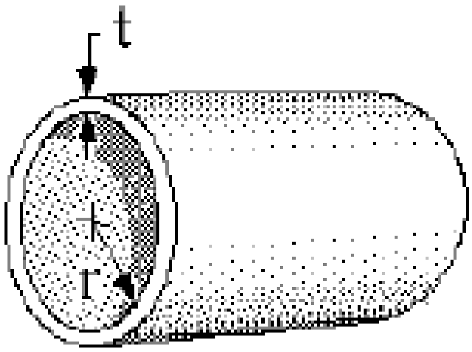

Figure 2.3: Ratio of pipe radius to pipe thickness

Source: Beer FP, Jr. Johnston ER, De Wolf JT (2006)

But, if the cylindrical pipe or pressure vessel has a ratio of $\frac{r}{t} \leq 10$, the cylinder can be considered as a thick-walled vessel and the hoop stress of the cylinder is equal to the tangential stress;

$$\sigma_t = \left[\frac{\left(p_i r_i^2 - p_o r_o^2\right)}{r_o^2 - r_i^2}\right] - \left[\frac{r_o^2 r_i^2 \left(p_o - p_i\right)}{r^2\left(r_o^2 - r_i^2\right)}\right] \tag{2.3}$$

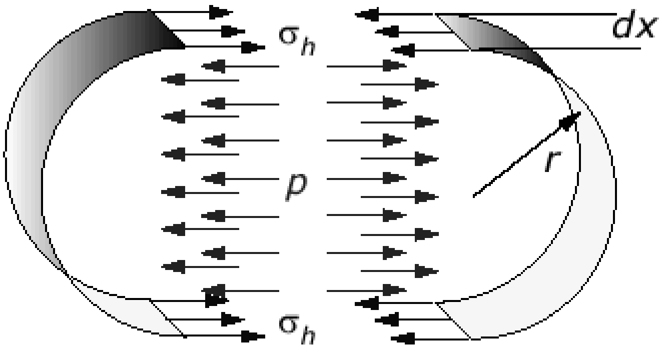

Figure 2.4: Hoop stress acted on steel pipe

Source: Beer FP, Jr. Johnston ER, De Wolf JT (2006)

2.5.2 Radial Stress

When the assumption for thin wall states that if $\frac{r}{t} \geq 10$, the ratio of the internal radius of the pipe and the thickness is less than 10. The stress acted on the z axis is equal to zero (0), $\sigma_z = 0$, and thus the radial stress σ_r will also equal to zero $\sigma_r = 0$ because the radial stress acted on the pipe is rotated along the z-axis.

2.5.3 Axial Stress

Defined as, the tension or compression stress created in a structural member by the application of a lengthwise axial load. Sometimes, axial stress also called as longitudinal stress.

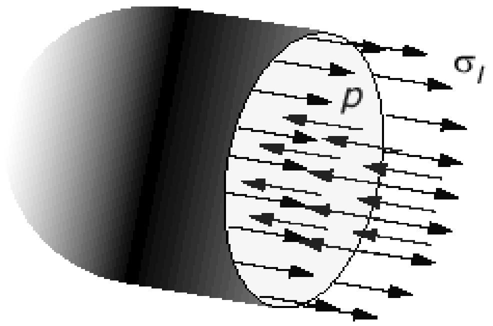

Figure 2.5: Longitudinal stress acted on steel pipe

Source: Beer FP, Jr. Johnston ER, De Wolf JT (2006)

To determine the longitudinal stress σ_l, we make a cut across the cylinder similar to analyzing the spherical pressure vessel. The free body, illustrated on the above, is in static equilibrium. This implies that the stress around the wall must have a resultant to balance the internal pressure across the cross-section.

Applying Newton's first law of motion, we have,

$$\sigma_l \cdot t \cdot 2\pi r = p \cdot \pi r^2 \tag{2.4}$$

$$\sigma_l = \frac{pr}{2t} \tag{2.5}$$

The equation stated above can only be used if the pipe or pressure vessel is assumed as a thin-walled.

2.5.4 Burst Pressure of a Pipe

Burst pressure for direct definition is; maximum pressure. To be general, a defective pipe would have a lower burst pressure rather than a non-defective pipe. To be précised, it is a pressure limitation of a pipe can withstand before it damage/defective (without bursting). Burst pressure can be calculated by using Barlow's Formula.

$$P = \frac{2\,s\,t}{d_0\,SF} \tag{2.6}$$

With, s, for the material strength (MPa), t, wall thickness of pipe, d_0, is the outer diameter of the steel pipe, and SF, is the safety factor of the material which is usually 1.5 to 10. Equation (2.6) is based on ideal condition at room temperature with no defect on the pipe outer surface. Thus, ultimate tensile strength can be used to determine the bursting pressure and yield strength can be used at which the permanent deformation of the material begins.

2.6 THEORY

After all, the stresses acted on the steel pipe could not be determined by using the equations of hoop, radial and axial stress because the pipe has been gouged as a substitute to the defect on a steel pipe. Those stresses only applicable, if the pipe used was free of defects. In this analysis of determining the burst pressure of defective steel pipe, the Stress Modified Critical Strain (SMSC) approach was used, because it is more fundamental. SMSC approach was based on the analysis of the 'local' criterion. Noting that the process of ductile fracture involves void nucleation, growth and coalescence and it is strongly dependent on the hydrostatic stress state (Oh CK, Kim YJ, Baek JH, Kim WS, 2007). Failure initiates in the central region of the gouge where the stress state is most severe and different stress states can be obtained with gouge of different severity